An Investigation on the Effects of Non-Gaussian Noise Transients and Their Mitigations to Tests of General Relativity

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August 28, 2020

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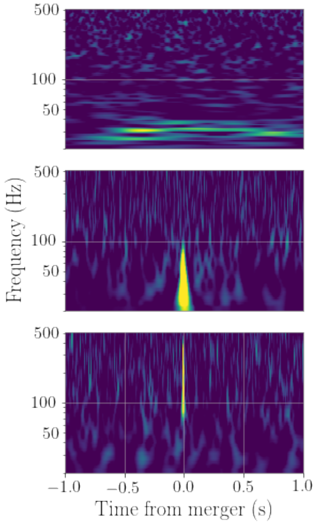
Motivation

Non-Gaussian Noise Transients (Glitches)

- Mimic GW signals in searches
- Bias inference of source properties of gravitational waves (GW)
- Expected to produce false violations of General Relativity



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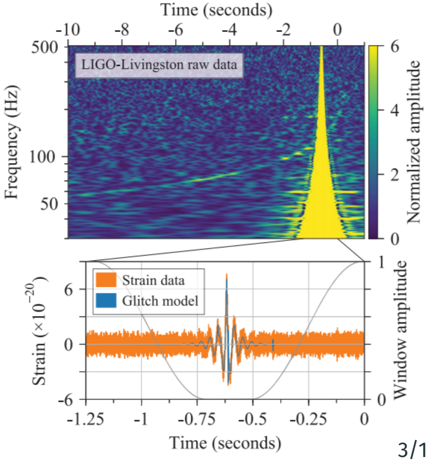
A glitch overlapped with the GW170817 signal in Livingston

- Data was manipulated to remove the glitch
- Lead to false violations of General Relativity?



(Figure retrieved from GW170817 Discovery paper)

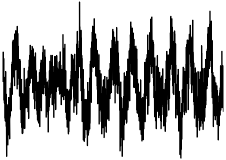
Outline

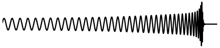
1. Introduction to GW Data Analysis
2. Parameterized Tests of General Relativity
3. Methodology
4. Example: Scattered-light Glitch

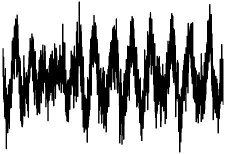
Introduction to GW Data Analysis

Data Model

$$\underbrace{\boldsymbol{d}(t_i)}_{\text{Detector strain}} = \underbrace{\boldsymbol{h}(\boldsymbol{\theta}; t_i)}_{\text{GW signal}} + \underbrace{\boldsymbol{n}(t_i)}_{\text{Stationary Gaussian noise}}$$







(Design courtesy of Cornish)

Bayesian Inference

$$P(\boldsymbol{\theta}|\boldsymbol{d}) \propto P(\boldsymbol{\theta}) \times P(\boldsymbol{d}|\boldsymbol{\theta})$$

(Bayes' Theorem)

$$= P(\boldsymbol{\theta}) \times \frac{1}{\sqrt{(2\pi)^N|\boldsymbol{\Sigma}|}} e^{-\frac{1}{2}(\boldsymbol{d}-\boldsymbol{h}(\boldsymbol{\theta}))^T \boldsymbol{\Sigma}^{-1}(\boldsymbol{d}-\boldsymbol{h}(\boldsymbol{\theta}))}$$

(Gaussianity, stationarity: $\Sigma_{ij} = \langle n(t_i)n(t_j)\rangle =$ constant)

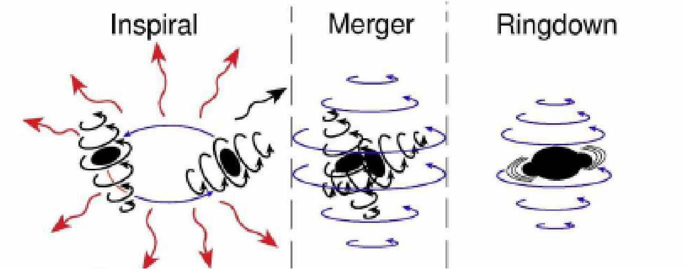
$$\propto\!\!\!\!\sim P(\boldsymbol{\theta}) \times \prod^{\substack{\text{frequency}\\\text{bins}}} \exp\left(-2\frac{|\tilde{d}(f_j) - \tilde{h}(\theta; f_j)|^2}{S_n(f_j)}\Delta f\right)$$

(Uncorrelated samples in Fourier Domain)

Parameterized Tests of General Relativity (GR)

Testing GR with Binary-Black-Hole Coalescence

- Clean Test
- Well Modeled
- Strong-field, highly dynamical

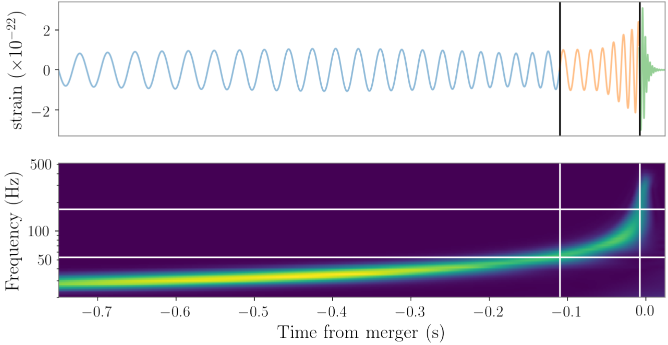


(Figure courtesy of Thorne)

Parameterized Tests of General Relativity

Introduce parameterized deviations to the phase Ψ of `IMRPhenomPv2`

$$\Psi(f) = \underbrace{\begin{matrix} \varphi_0(1+\delta\varphi_0)f^{-5/3} + (\varphi_1+\delta\varphi_1)f^{-4/3} + \varphi_2(1+\delta\varphi_2)f^{-1} + \varphi_3(1+\delta\varphi_3)f^{-2/3} + \varphi_4(1+\delta\varphi_4)f^{-1/3} \\ + \varphi_5 f^0 + \varphi_6(1+\delta\varphi_6)f^{1/3} + \varphi_7(1+\delta\varphi_7)f^{2/3} + \varphi_5^l(1+\delta\varphi_5^l)\log(f) + \varphi_6^l(1+\delta\varphi_6^l)f^{1/3}\log(f) \\ + \sigma_0 f^0 + \sigma_1 f + \sigma_2 f^{4/3} + \sigma_3 f^{5/3} + \sigma_4 f^2 \end{matrix}}_{\text{Inspiral}} + \beta \ldots + \beta \ldots$$



Parameterized Tests of General Relativity

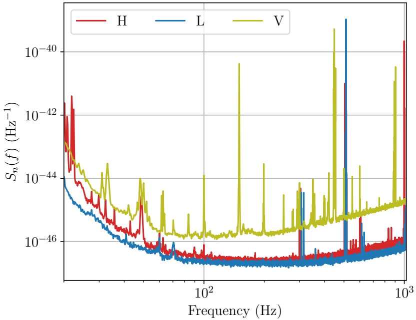
Deviation is introduced one parameter at a time:

$$P(\boldsymbol{h}(\theta, \delta p_i)|\boldsymbol{d})$$

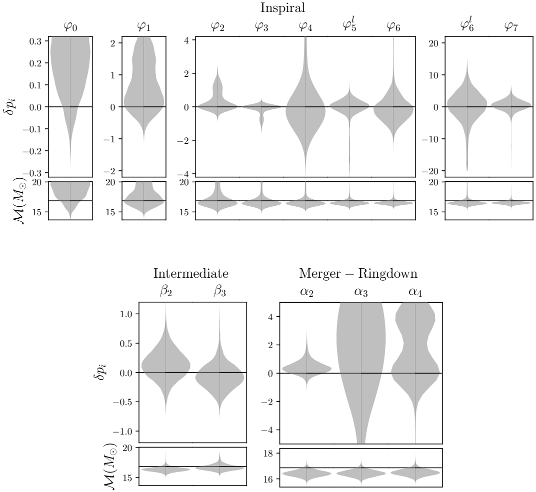
We report the marginalized posterior distribution of the introduced testing parameter:

$$P(\delta p_i|\boldsymbol{d}) = \int P(\boldsymbol{h}(\theta, \delta p_i)|\boldsymbol{d}) d\theta$$

Test Results in Colored Stationary Gaussian Noise



Representative best (cleaned) PSD for the Hanford (H), Livingston (L) and Virgo (V) detectors in observing run O3a are used to color simulated stationary Gaussian noise



Methodology

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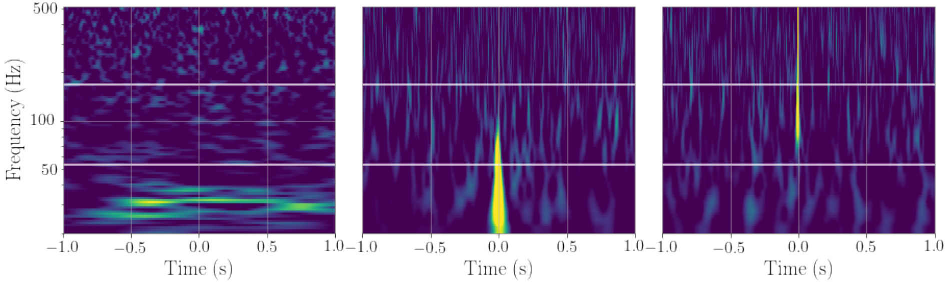
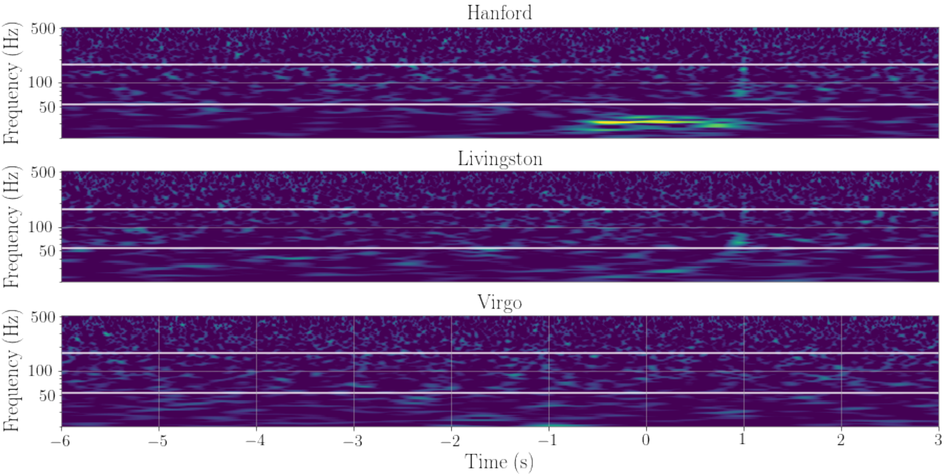
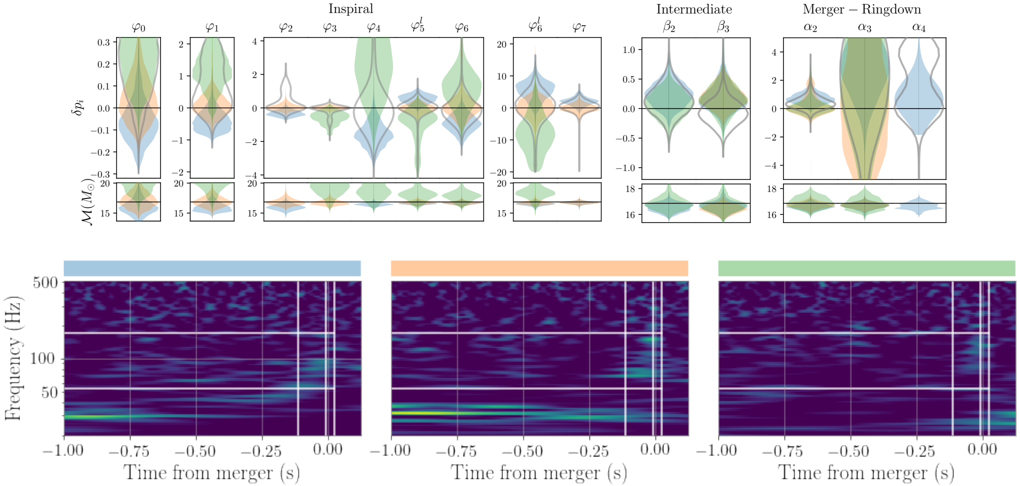


Methodology

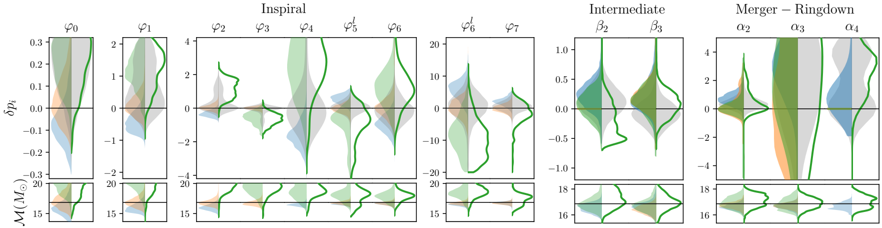


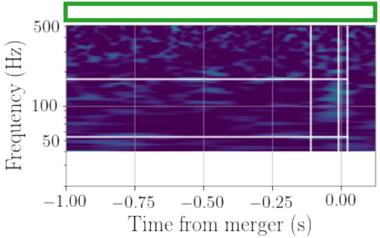
Example: Scattered-light Glitch

Effect of a Scattered-light Glitch

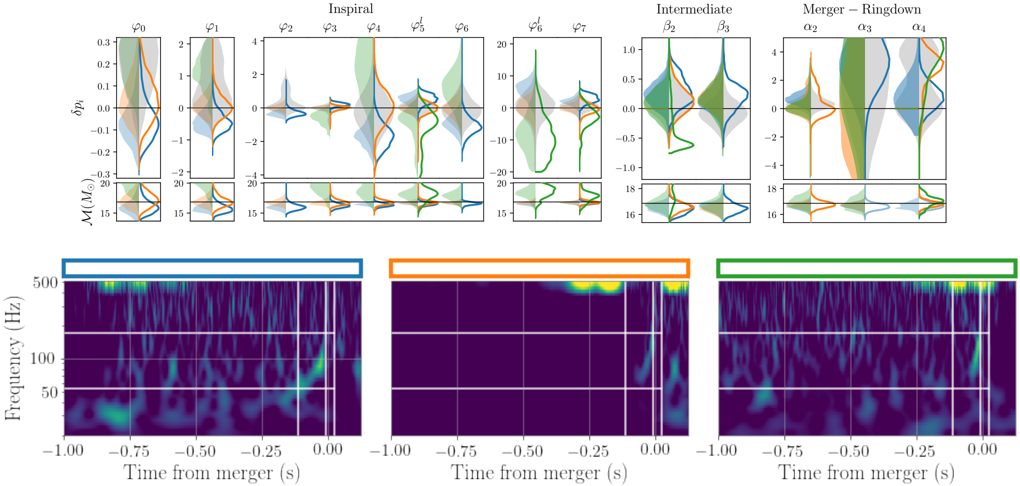


Effect of Masking frequency-bins (below 40 Hz)

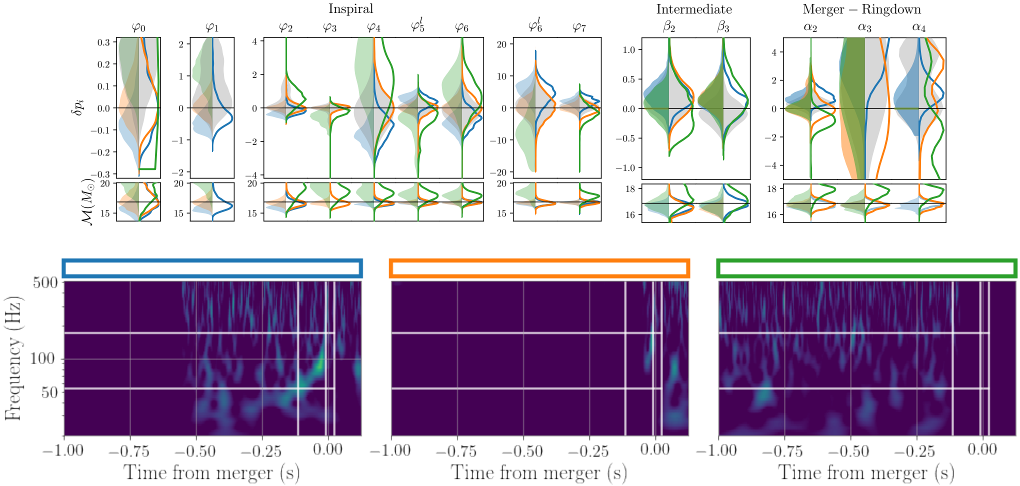




Effect of Masking affected time-bins



Effect of Inpainting



Conclusion

From our preliminary results on a scattered-light glitch:

- For most cases, a false deviation of GR due to the glitch cannot be identified when signal is injected in three detectors
- Overlapping the glitch with the merger-ringdown in time leads to bias in chirp mass measurement and shifts posterior away from zero for inspiral testing parameters
- Mitigation of the glitch overlapping the inspiral, intermediate in time has little to no effect on the posterior distribution of the testing parameters
- Mitigation of the glitch overlapping the merger-ringdown in time affects $\delta\beta_2$.
- Removing both the intermediate and merger-ringdown through inpainting leads to bias in chirp mass measurement and shifts posterior away from zero for merger-ringdown testing parameters.

Future work

On-going work:

- Reduce statistical uncertainty of the result in stationary Gaussian noise
- Study the effect of intermediate- and merger-ringdown-frequency glitch on Tests of GR
- Study the effect of `BayesWave` glitch subtraction on Tests of GR

Future work:

- Repeat the investigation for other types of GW signals (BNS, BHNS)
- Repeat the investigation using only data from two detectors

Acknowledgment

- LIGO Laboratories, National Science Foundation (NSF), NSF REU Program
- My LIGO mentors: Alan and Rico
- My CUHK mentor: Tjonnie
- Team Glitch
- My colleagues

and thank you for listening!

Questions?

Appendix

Effect of Tomte Glitch (Unmitigated)